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David C Larbalestier and Alex Gurevich

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Applied Superconductivity Center, National High Magnetic Field Laboratory, Florida State University
2031 East Paul Dirac Drive, Tallahassee FL 32310

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14. ABSTRACT

In early 2008 the Hosono group at Tokyo Institute of Technology discovered high temperature superconductivity in a new extensive family of pnictides based on doped As-Fe. This exciting discovery encouraged us to transition our work on grain boundary studies of YBCO to this new class of superconductors. We showed that they indeed exhibit high critical temperatures T_c, extremely high upper critical fields H_{c2}, an irreversibility field H^* close to H_{c2}, high critical current density J_c, and small electronic anisotropy $\gamma = H_{c2}^{ab}/H_{c2}^{c}$. Our recent pioneering investigation of 122 bicrystals has shown that grain boundaries in pnictides exhibit weak link behavior similar to that of cuprates. Moreover, our recent experiments introducing controlled magnetic and nonmagnetic disorder by α particle irradiation have shown a remarkable resilience of multiband superconductivity to nonmagnetic and Kondo scattering, suggesting new possibilities of their optimization. In this respect the pnictides are both similar and rather dissimilar to the cuprates, issues that deserve understanding since doping from an initial non-superconducting state is so far the only way to achieve a transition temperature of more than 50 K.

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Summary of work carried out in 2009-2010 under AFOSR grant - FA9550-06-1-0474

Principal Investigators David Larbalestier and Alex Gurevich
Applied Superconductivity Center
National High Magnetic Field Laboratory
Florida State University

The recently discovered pnictide superconductors belong to a very broad class of fascinating materials in which Cooper pairing is mediated by pair-breaking magnetic Fe^{2+} ions, which would normally be thought to suppress superconductivity. In these semi-metallic compounds, strong magnetic and Coulomb correlations and multiband effects are inherently connected to their superconductivity, resulting in T_c up to 55K. There are many striking similarities between pnictides and high-T_c cuprates, and, although the microscopic mechanisms of their superconductivity are far from being fully understood, pnictides serve as an important case study for new superconducting materials because they encapsulate some of the key ideas of high-T_c superconductivity that many hope will lead to even higher T_c, perhaps even room-temperature superconductivity. Given the ongoing intense investigation of pnictides in many labs worldwide, there is also a chance that higher-T_c pnictides may be discovered. Even at this early stage, it is already clear that the enormously high H_{c2} of pnictides (extrapolating to >100 T), high irreversibility field and very strong vortex nanopillars pinning resulting in very high J_c are all very attractive qualities. Precisely because the subtle mechanisms of superconductivity in cuprates and pnictides are so hard to unravel, it is of great importance to understand them, especially whether the doped antiferromagnetic multilayer structure of pnictides and cuprates represents the best (it is so far the only working one) paradigm for high T_c superconductivity. Tuning the doping state, modifying the impurity scattering and the anisotropy by controlled defect introduction can increase T_c and J_c. Our work has been motivated by the following key questions:

1. What is the nature of the pairing mechanism in the pnictides and what controls T_c and H_{c2}?
2. How do impurities affect T_c and H_{c2} and what is the interplay between magnetism and superconductivity?
3. Can the electronic anisotropy of the layered pnictides be tuned by alloying or controlled defect introduction? What effect does the anisotropy have on vortex dynamics, the critical current density J_c and the irreversibility field *H*?*
4. Do grain boundaries (GBs) block current and can their properties be improved by doping?
5. Can artificial pinning nanostructures and crystal texturing be introduced to enhance vortex pinning, reduce thermal fluctuations of vortices and ameliorate weak-linked GBs?

The ASC-NHMFL group working with other groups (Arizona State, U. of Wisconsin, ORNL, LANL, U of Michigan, Ohio State, CAS-Beijing) has pioneered key experiments in which some of these questions have been addressed. Among our main results are:

1. We were the first to show the extremely high H_{c2} in pnictides (well above the BCS paramagnetic limit) and pointed out the importance of multiband effects on the anomalous temperature dependence of H_{c2} and vortex dynamics and pinning. *(Hunte et al. Nature 2008).*
2. We were the first to show the weak linked GBs in pnictide bicrystals (made by C-B Eom group at UW) and revealed a universal behavior of GBs in controlling current transport in cuprates and pnictides. *(Lee et al. Appl. Phys. Letts, 2009).*
3. We were the first to show the intriguing effect of controlled disorder induced by □-particle irradiation (in collaboration with the group of N. Newman at ASU and Hai-Hu Wen at CAS-Beijing). We found a surprising resilience of superconductivity in pnictides to dense magnetic and nonmagnetic irradiation disorder, despite strong Kondo scattering induced by irradiation. *(Tarantini et al. Phys. Rev. Letts. 2010).*

4. In collaboration with the groups at UW and Michigan, we have developed a novel method of template engineering, which enabled us to simultaneously make films of the highest yet crystal quality while introducing nanopillars which are dense and almost exactly a vortex core in diameter and thus yield exceptionally strong vortex pinning. *(Lee et al. Nature materials 2010 and Tarantini et al. Appl. Phys. Letts. 2010).*
5. Our very recent high-field pulse measurements at LANL (up to 85T) have shown that H_{c2} in 11 and underdoped 122 films is mostly paramagnetically limited, indicating a possibility of the inhomogeneous Fulde-Ferrel-Larkin-Ovchinnikov state at high fields and low temperatures. *(Tarantini et al. in preparation)*.

The results of our work have been published in 23 journal papers (+ 3 submitted) and presented by the PIs in 34 invited talks in 2009-2010. Given our unique capability to unite the NHMFL high-field facilities with a variety of advanced characterization techniques (electron microscopy, MOI, transport, LTLSM, magnetization, specific heat, and others) and bulk materials fabrication (samples for bulks, for PLD targets and single crystals), augmented by our close collaboration with several key research groups (C-B Eom at UW, H-H. Wen at Beijing, M. Putti at Genoa and others), ASC is very well positioned to continue our successful work on pnictides. We believe that the true potential of pnictides has been hardly realized and plan to understand the fundamental physics of superconductivity in pnictides and use nanoscale defect engineering to develop better materials with higher T_c, J_c and H* and lower anisotropy.

ASC Pnictide papers 2008-2010

1. F. Hunte, J. Jaroszynski, A. Gurevich, D.C. Larbalestier, R. Jin, A.S. Sefat, M.A. McGuire, B.C. Sales, D.K. Christen and D. Mandrus, "Two-band superconductivity in $LaFeAsO_{0.89}F_{0.11}$ at very high magnetic fields", *Nature*, **453**, 903 (2008).
2. J. Jaroszynski, F. Hunte, L. Balicas, Y.-J. Jo, I. Raicevic, A. Gurevich, D.C. Larbalestier, F.F. Balakirev, Y. Jia, P. Cheng, L. Fang, H. Luo, H. Yang, C. Ren, L. Shan, C. Gu and H.H. Wen, "Upper Critical Fields and Thermally-Activated Transport of $Nd(O_{0.7}F_{0.3})FeAs$ Single Crystal", *Phys. Rev. B*, **78**, 174523 (2008).
3. J. Jaroszynski, S.C. Riggs, F. Hunte, A. Gurevich, D.C. Larbalestier, G.S. Boebinger, F.F. Balakirev, A. Migliori, Z.A. Ren, W. Lu, J. Yang, X.L. Shen, X.L. Dong, Z.X. Zhao, R. Jin, A.S. Sefat, M.A. McGuire, B.C. Sales, D.K. Christen and D. Mandrus, "Comparative High-Field Magnetotransport of the Oxypnictide Superconductors $RFeAsO_{1-x}F_x$ (R=La, Nd) and $SmFeAsO_{1-x}$", *Phys. Rev. B*, **78**, 064511 (2008).
4. C. Tarantini, A. Gurevich, F. Kametani, A. Yamamoto, D.C. Larbalestier, Z.A. Ren, X.L. Dong, W. Lu and Z.X. Zhao, "Paramagnetic Properties of $NdFeAsO_{0.94}F_{0.06}$ Polycrystals", *J. Phys. Soc. Japan*, **77**, 84 (2008) .
5. C. Tarantini, A. Gurevich, D.C. Larbalestier, Z.A. Ren, X.L. Dong, W. Lu and Z.X. Zhao, "Superconductivity and Antiferromagnetic Ordering in the High-Field Paramagnetic Oxypnictide $NdFeAsO_{0.94}F_{0.06}$", *Phys. Rev. B*,**78**, 184501 (2008).
6. A. Yamamoto, J. Jiang, C. Tarantini, N. Craig, A.A. Polyanskii, F. Kametani, F. Hunte, J. Jaroszynski, E.E. Hellstrom, D.C. Larbalestier, R. Jin, A.S. Sefat, M.A. McGuire, B.C. Sales, D.K. Christen and D. Mandrus, "Evidence for electromagnetic granularity in the polycrystalline iron-based superconductor $LaO_{0.89}F_{0.11}FeAs$", *Appl. Phys. Lett.*, **92**, 252501 (2008).
7. A. Yamamoto, A.A. Polyanskii, J. Jiang, F. Kametani, C. Tarantini, F. Hunte, J. Jaroszynski, E.E. Hellstrom, P.J. Lee, A. Gurevich, D.C. Larbalestier, Z.A. Ren, J. Yang, X.L. Dong, W. Lu and Z.X. Zhao, "Evidence for two distinct scales of current flow in polycrystalline Sm and Nd iron oxypnictides", *Superconductor Science and Technology*, **21**, 095008 (2008).

8. M.R. Cimberle, F. Canepa, M. Ferretti, A. Martinelli, A. Palenzona, A.S. Siri, C. Tarantini, M. Tropeano and C. Ferdeghini, "Magnetic characterization of undoped and 15%F doped LaFeAsO and SmFeAsO compounds", *J. Magn. Magn. Mater.,* **321** (19), 3024-3030 (2009).
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10. M. Eisterer, M. Zehetmayer, H. W. Weber, J. Jiang, J.D. Weiss, A. Yamamoto, and E. E. Hellstrom, "Effects of disorder on the superconducting properties of $BaFe_{1.8}Co_{0.2}As_2$ single crystals", *Superconductor Science and Technology*, **22**, 095011 (2009).
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12. F. Kametani, P. Li, D. Abraimov, A. A. Polyanskii, A. Yamamoto, J. Jiang, E. E. Hellstrom, A. Gurevich and D. C. Larbalestier, Z. A. Ren, J. Yang, X. L. Dong, W. Lu and Z. X. Zhao, "Intergrain current flow in a randomly oriented polycrystalline $SmFeAsO_{0.85}$ oxypnictide", *Appl. Phys. Letts.*, **95**, 142502 (2009).
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15. S. Riggs, C. Tarantini, J. Jaroszynski, A. A. Gurevich, Palenzona, M. Putti, T. Duc Nguyen and M. Affronte, "Specific heat investigation in high magnetic field of the magnetic ordering of the rare-earth lattice in RFeAsO: The case of Sm", *Phys. Rev. B*, **80**, 214404 (2009).
16. A. Yamamoto, J. Jaroszynski, C. Tarantini, L. Balicas, J. Jiang, A. Gurevich, and D.C. Larbalestier, R. Jin, A.S. Sefat, M.A. McGuire, B.C. Sales, D.K. Christen, and D. Mandrus, "Small anisotropy, weak thermal fluctuations, and high field superconductivity in Co-doped iron pnictide $Ba(F_{e1-x}C_{ox)2}A_{s2}$", *Appl. Phys. Lett**s***, **94**, 062511 (2009).
17. A. Yamamoto, J. Jiang, C. Tarantini, N. Craig, A. A. Polyanskii, F. Kametani, F. Hunte, J. Jaroszynski, E. E. Hellstrom, D. C. Larbalestier, R. Jin, A. S. Sefat, M.A. McGuire, B. Sales, D. K. Christen and D. Mandrus, "Evidence for electromagnetic granularity in the polycrystalline iron-based superconductor $LaO_{0.89}F_{0.11}FeAs$", *Appl. Phys. Letts.*, **252,** 252501 (2009).
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19. C. Tarantini, M. Putti, A. Gurevich, Y. Shen, R.K. Singh, J.M. Rowell, N. Newman, D.C. Larbalestier, Peng Cheng, Ying Jia, Hai-Hu Wen "Suppression of the critical temperature of superconducting NdFeAs(OF) single crystals by Kondo-like defect sites induced by α-particle irradiation", *Phys. Rev. Lett.*, **104**, 087002 (2010).
20. A. Yamamoto, A. Gurevich, D. Larbalestier, J. Shimoyama and K. Kishio, "Grain Boundary and Critical Current of MgB_2 and Iron Pnictide Superconductors," *OYO BUTURI*, **79**, 48-53 (2010). (in Japanese)
21. S. Lee, J. Jiang, C. Nelson, C. Bark, J. Weiss, C. Tarantini, H. Jang, C. Folkman, S. Baek, A. Polyanskii, D. Abraimov, A. Yamamoto, Y. Zhang, X. Pan, E. Hellstrom, D. Larbalestier and C. Eom,

"Template engineering of Co-doped $BaFe_2As_2$ single-crystal thin films ", *Nature Materials*, **9**, 397 (2010)

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23. M. Eisterer, M. Zehetmayer, H. W. Weber, J. Jiang, J. D. Weiss, A. Yamamoto, E. E. Hellstrom, D. C. Larbalestier, N. D. Zhigadlo and J. Karpinski, "Disorder effects and current percolation in FeAs-based superconductors", *Superconductor Science and Technology*, **23**, 054006 (2010).
24. A. Perucchi, L. Baldassarre, C. Marini, S. Lupi, J. Jiang, M. Putti, I. Pallecchi, J.D. Weiss, E. E. Hellstrom, S. Lee, C.W. Bark, C. B. Eom, and P. Dore, "Multi-gap superconductivity in a $BaFe_{1:84}Co_{0:16}As_2$ film from optical measurements at terahertz frequencies" submitted to EuroPhysics Letters (2010)
25. G. Sheet, M. Mehta, D. A. Dikin, S. Lee, C.W. Bark, J. Jiang, J. D. Weiss, E. E. Hellstrom, M.S. Rzchowski, C.B. Eom and V. Chandrasekhar, "Phase-incoherent superconducting pairs in the normal state of $Ba(Fe1\text{-}xCox)_2As_2$", submitted to Science (2010)
26. Yi Zhang, Christopher T. Nelson, Sanghan Lee, Jianyi Jiang, Chung Wung Bark, Jeremy D. Weiss, Chiara Tarantini, Chad M. Folkman, Seung-Hyub Baek, Eric E. Hellstrom, David C. Larbalestier, Chang-Beom Eom, Xiaoqing Pan, "Self-Assembled Oxide Nanopillars in Epitaxial Co-doped $BaFe_2As_2$ Thin Films for Vortex Pinning", submitted to Nanoletters.

Invited Talks on Pnictides and Broader Issues by the PIs during 2009-2010

1. A. Gurevich. "Superconductivity in oxypnictides". Old Dominion University. Physics Colloquium, March 31, 2009.
2. A. Gurevich. "Oxypnictide superconductors at high magnetic fields". 2009 Spring Meeting of Materials Research Society, San Francisco, April 14-16, 2009.
3. A. Gurevich. "Tailoring designer superconductors for power applications." International Workshop on the search for New Superconductors, Japan, May 12-16, 2009.
4. A. Gurevich. "Pnictides at high magnetic fields". KITP School on High-Tc superconductivity, Santa Barbara, August 12, 2009
5. A. Gurevich. "Designing superconducting materials for applications." Summer School for New Superconducting Materials, University of Santa Barbara, August 7, 2009.
6. A. Gurevich. "Making cuprates and other new superconductors suitable for applications." Materials and Mechanisms of Superconductivity, Tokyo, Japan, September 11, 2009 (plenary talk).
7. A. Gurevich. "Ultrafast dynamics of vortex penetration and nonlinear surface resistance under strong rf fields". 12th International Workshop on Vortex Matter in Superconductors, Lake Yamanaka, Japan, Sept. 12-16, 2009.
8. A. Gurevich. "Making cuprates and other new superconductors suitable for applications." Dept. of Physics, University of Florida, Gainesville, Sept. 28, 2009.
9. A. Gurevich. "High field superconductivity in ferropnictides", LANL, Oct. 14, 2009.
10. A. Gurevich. "Effect of defects on the physics of SRF", 6-th Materials SRF Workshop. NHMFL, Tallahassee, February 19-20, 2010.
11. A. Gurevich. "Ferropnictides at high magnetic fields: the role of pairing symmetry and impurity scattering", APS March Meeting, Portland, OR, March 16, 2010.
12. A. Gurevich. "Impurity effects and current transport in oxypnictides at high magnetic fields" International Conference of Superconductivity and Magnetism, Antalya, Turkey, April 25-30, 201

13. David Larbalestier, “Potential for Superconducting Magnets above 30T”, Bruker Advanced Superconductor, Hanau Germany, February 10, 2009.
14. David Larbalestier, “Superconductors for Accelerator Use: What next and how close is the ideal conductor?”, Fermilab Colloquium, February 24, 2009
15. David Larbalestier, “Potential for Superconducting Magnets above 30T”, Bruker Advanced Superconductor, Hanau Germany, February 10, 2009.
16. David Larbalestier, “Superconductors for Accelerator Use: What next and how close is the ideal conductor?”, Fermilab Colloquium, February 24, 2009
17. David Larbalestier, Superconductors for future high field use: Why not multifilamentary YBCO - or something even better?, CEA Cadarache , March 23, 2009.
18. David Larbalestier, “Pushing the still unknown of Nb_3Sn – a strand level view”, ITER Strand and Cable Review meeting Cadarache France, March 24, 2009.
19. David Larbalestier, “Recent Adventures in HTS at the NHMFL”, Association Francais du Froid, Aussois, France March 25, 2009.
20. David Larbalestier, “Superconductors for future high field use: Why not multifilamentary YBCO - or something even better?”, British Cryogenics Council Lecture, Clarendon Laboratory, Oxford University, Oxford , UK, March 30, 2009.
21. David Larbalestier, “Some thoughts on the scientific impact of Masaki Suenaga to Superconducting Materials”, Masaki Suenaga Memorial Symposium, Brookhaven National Laboratory, May 29, 2009.
22. David Larbalestier, “Superconductors for future high field use: Why not multifilamentary YBCO - or something even better?”, Institute for Technical Physics Colloquium, Research Center Karlsruhe, Germany, September 8, 2009.
23. David Larbalestier, “High Temperature Superconductors for High Field Use”, 12th International School on Fusion Reactor Technology, Erice Italy, September 9-16, 2009.
24. David Larbalestier, “Are there routes to a round wire multifilament high Tc conductor?”, European Conference on Applied Superconductivity (EUCAS), Dresden, Germany, September 14-18, 2009.
25. David Larbalestier, “A reflection on the influence of Masaki Suenaga on the understanding and applications of the A15 compounds and other low temperature superconductors”, International Symposium on Superconductivity ISS’09, Tsukuba Japan, November 2-4, 2009.
26. David Larbalestier, “Prospects for the development of round wire multifilament forms of High Temperature Superconductors conductors”, International Symposium on Superconductivity (ISS’09), Tsukuba Japan, November 2-4, 2009.
27. David Larbalestier, “High Field Magnets with YBCO coated conductors”, CCA '09 Coated Conductors for Applications, Barcelona, Spain, Nov. 22-24 (2009).
28. David Larbalestier, “Is what we really want from YBCO possible – a multifilament, round-wire conductor?, CCA '09 Coated Conductors for Applications, Barcelona, Spain, Nov. 22-24 (2009).
29. David Larbalestier, “Prospects for High Field Superconducting Magnets made from High Temperature Superconductors”, ISIS 18, Wellington NZ, February 9, 2010.
30. David Larbalestier, “Grain boundaries in cuprates and pnictides: are there reasonable hopes for better properties”, Condensed Matter and Materials Science Division Seminar, Brookhaven National Laboratory, March 1, 2010.
31. David Larbalestier, “Superconductors for High Magnetic Fields”, Physics Department Colloquium, Stony Brook University, March 2, 2010.
32. David Larbalestier,” Transformational Opportunities of YBCO/REBCO for Magnet Technology”, 10^{th} Anniversary Symposium for SuperPower, Schenectady NY, March 15, 2010.
33. David Larbalestier, “Grain boundaries in cuprates and pnictides: are there reasonable hopes for better properties”, Opening Talk to the Spring MRS Symposium on Superconductivity, San Francisco, CA, April 6-9, 2010.

34. David Larbalestier, “Applications for YBCO in magnets”, Wire Workshop, Houston TX, June 4-5, 2010.